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MATERIAL AND OPERATIONAL PROPERTIES OF LARGE-AREA MEMBRANE TYPE SENSORS FOR SMART ENVIRONMENTS

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Abstract – Certain plastic film materials can be used as sensitive tactile and impact sensors covering large surfaces. In surveillance and health care applications they can sense movement, activity or some physiological parameters. Various available film materials and their operational principles are reviewed. Comparison has been made between piezoelectric polymer film, thin porous electret material, and soft capacitive film materials in their sensing capabilities. Generation of the signal and measurement instrumentation for different sensor configurations is discussed. The structure and properties of a voided polypropylene film material and some applications and measurement results are presented. It can be shown that especially in large area applications the electret type porous films show several benefits when compared with the other solutions.

Keywords: sensor, electret, EMFi

1. INTRODUCTION

In the visions of smart environments and ubiquitous computing the surrounding space and appliances will sense the behavioural activity of users and adjust their own operations or control system accordingly. There are different ways how this kind of unobtrusive sensing can be realised. One way is to include sensing properties in ordinary materials and structures by utilising thin smart polymer materials.

Piezoelectric polymers, like PVDF (polyvinylidene fluoride), have been used for pressure and force sensing applications. There are piezoelectric film sensors and material commercially available [1]. A new group of sensing materials is the porous electrets. The soft materials contain charged microscopic voids and show very high quasi-piezoelectric response and electromechanical coefficients [2, 3]. Polymeric tactile sensor materials based on either capacitive or resistive principle have been used in touch screens and keypads.

However, in most of the sensors that are commercially available the sensing areas are rather small. For large areas like floors, corridors, walls, tables or chairs a special sensor material is needed. The material should be inexpensive, thin, durable and sensitive enough. Also the film manufacturing should be economical, so that covering of large areas can be realised with a reasonable price.

In this paper we review and present a comparison between different sensing materials suitable for surveillance and security monitoring, tactile and impact sensors, future user interfaces, and smart environment applications.

2. SENSOR MATERIALS

Polymer film materials are promising for large-area applications, because they can be mass-produced. However, the mechanical and electrical properties of the materials have to be optimised for sensing applications. Also electrically conducting electrode layers at both surfaces of the film are needed.

2.1. Piezoelectric polymers

The manufacturing techniques of piezoelectric polymers include extrusion and stretching in a strong electrical polarization field. Typical piezoelectric coefficients for PVDF are $d_{33} = -33\ pCN^{-1}$ and $d_{31} = 23\ pCN^{-1}$ [1]. Thus, the material is sensitive to strain both in film thickness and length directions. The vast dynamic range covers pressures from 1 μPa to 5 GPa. A PVDF film sensor glued on a surface is sensitive to compressive force but at the same time also to bending of the surface. To distinguish signal between these two modes might be difficult. PVDF is highly sensitive to temperature with a pyroelectric coefficient of $10^{-6}\ Cm^{-2}K^{-1}$. This property can be used in motion sensors but it might create problems in signal analysis of low frequency pressure or force measurements. Highly sensitive piezoelectric materials usually contain fluorine that is a potentially toxic substance, which can be considered as a great disadvantage.

2.2. Porous electret materials

A procedure for producing cellular polypropylene films was started during the 1980s at the Tampere University of Technology in Finland [4], and has been further developed at VTT [5]. The ElectroMechanical Film (EMFi) is manufactured in a biaxial orientation process, which produces flat air voids in the material, Fig. 1. Having this special internal structure and high resistivity, it is capable of storing large permanent charge. The charge is injected by a corona method using higher than 10 kV cm^{-1} fields. The material shows a strong quasi-piezoelectric response when compressed. The electro-mechanical coefficients of EMFi are typically d_{33} = 170 pCN^{-1} and d_{31} = 2 pCN^{-1} [6, 7, 8]. Thus, the sensitivity in the film thickness direction is very high, but in the lateral directions (stretching) only about 1% of that [6]. The maximum pressure that can be measured by using the voided structure of EMFi is around 1 MPa. Porous polypropylene, like all plastics, is also somewhat sensitive to temperature. The dependence of the d_{33} coefficient on temperature is 0.36 $pCN^{-1}K^{-1}$ under the glass transition temperature and 2.2 $pCN^{-1}K^{-1}$ above it [6].

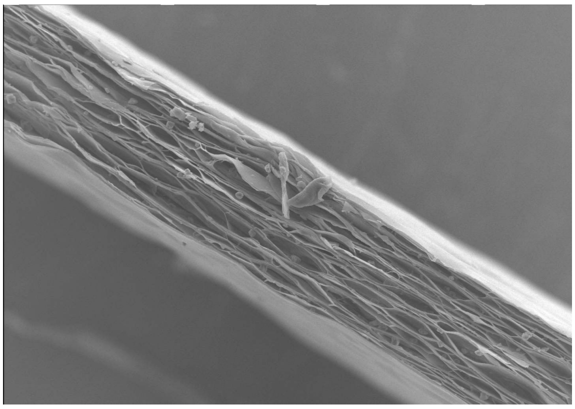

Fig. 1. Scanning electron microscope picture of the cross-section of a 70-µm thick porous electret film (EMFi). Both surfaces are covered with thin metal electrodes.

2.3. Capacitive films

Practically any dielectric film with some elasticity and proper dielectric properties can be used as a capacitive sensor. Changes in film thickness caused by compression due to the exerted force are monitored. Special readout electronics is, however, needed. The sensitivity depends on the electrical and mechanical properties of the material and also on the measurement configuration.

3. OPERATIONAL PROPERTIES

There are basic differences in signal generation and realisation of measurement systems between piezoelectric, porous electret, and capacitive sensing films. Especially in large area applications the electret type porous films show superior properties when compared with the other solutions.

3.1. Signal generation

Piezo polymer and porous electret film materials behave like a capacitive generator type sensors giving output signal without any external electric excitation, Fig. 2. This simplifies the measurement configuration and read-out electronics. The charge signal ΔQ at the electrodes is proportional to the dynamic force ΔF exerted to film surface. The signal voltage across the sensor film is

$$\Delta V = \frac{\Delta Q}{C_s} = \frac{d_{33}\Delta F}{C_s} \qquad (1)$$

where d_{33} is the electromechanical or piezoelectric coefficient

$$d_{33} = \frac{\Delta\sigma}{\Delta p} = \frac{\Delta Q}{\Delta F} \qquad (2)$$

and C_s is the capacitance of the sensor film. Δσ is the change of the charge density on the electrodes and Δp = $\Delta F/A_d$ is the amplitude of the dynamic pressure within the area A_d where the force is acting. According to the equation 1 the voltage signal is inversely proportional to the capacitance of the sensor. This means that the voltage signal is high when the sensor area is small.

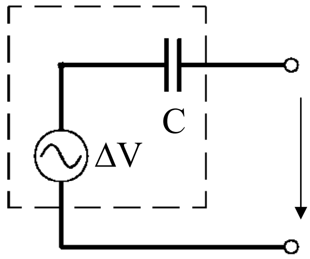

Fig. 2. Active sensing film can be modelled as a capacitive voltage generator.

A passive capacitive sensing film behaves like a modulator type sensor, and thus needs electronic excitation that probes the capacitance. In a bridge type measurement the output signal is proportional to the relative change of the film capacitance

$$\frac{\Delta C_s}{C_s} = \left(1 - \frac{x}{x - \Delta x}\right)\frac{A_d}{A_0} \qquad (3)$$

where x is the thickness and A_0 the total area of the film sensor, Δx is the change of the thickness of the film caused by the external force within the area A_d ($A_d \leq A_0$). The thickness change Δx of the film depends on the force exerted and the Young's modulus of the film material.

One difference between the sensor types mentioned above is that the piezoelectric and electret sensors measure only dynamic forces, whereas a capacitive film sensor can also be used for detection of a static force, like the weight of an object.

TABLE I. Comparison between three different sensing film materials.

Property	Piezoelectric Film (PVDF)	Porous Electret Film (EMFi)	Soft dielectric film
Sensor type	generator	generator	modulator
Response	dynamic	dynamic	static
Sensitivity axes	d_{33}, d_{31}	d_{33}	thickness
Rel. sensitivity	10	100	1-10
Dynamic range	14 decades	8 decades	varies
Relative price	100	10 - 30	1

3.3. Large area sensors

If a film-sensor is used for large area applications, like surveillance monitoring at a floor, the benefits of a generator type sensor are obvious. In the piezoelectric and electret sensors the generated charge can be measured with a charge amplifier. In this case the film sensor is short-circuited and the size of the sensor does not have effect on the measured signal amplitude. In the case of capacitive sensor-films the signal (3) depends on the thickness change Δx, and the ratio between the area of the total sensor A_0 and the area A_d where the force or pressure is acting. If the thickness change and A_d/A_0-ratio are small, the relative change of the capacitance can be very small.

3.2. Amplifiers

There are two basic approaches when designing pre-amplifiers for piezoelectric and electret type sensors. We can use a voltage amplifier with high input impedance or a charge amplifier that short-circuits the capacitive source.

In the case of voltage amplifier the high-pass frequency of the filter formed by the sensor-amplifier system is

$$f_{HP} = \frac{1}{2\pi R_{in} C_s} \quad (4)$$

where R_{in} is the input resistance of the amplifier. For a small sensor (small C_s value) we need an amplifier with a very high input impedance to keep the cut-off frequency low enough and bandwidth wide. The higher cut-off frequency of the system normally depends only on the properties of the amplifier used.

In the case of a charge amplifier the high-pass frequency of the system depends of the feedback capacitor C_f and resistor R_f of the amplifier, Fig. 3.

$$f_{HP} = \frac{1}{2\pi R_f C_f} \quad (5)$$

Because the sensor is short-circuited its capacitance C_s (and thus also size) does not affect. The amplifier acts as a charge amplifier (integrator) above the cut-off frequency f_{HP} and as a current amplifier below that frequency. With this kind of amplifier it is easier to design a proper measurement frequency range also for large area sensors (large capacitance). Additional low-pass filter section can be used at the output of the amplifier to limit the bandwidth.

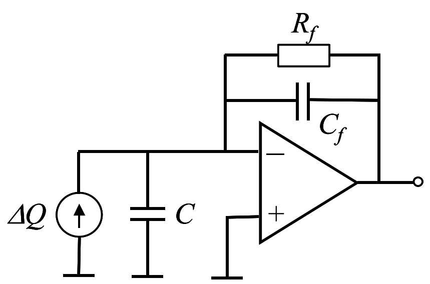

Fig. 3. Charge amplifier for a capacitive generator type source.

3.4. Location sensitive solutions

Film sensors that are able to locate the acting point of a force or a moving object can be realized in many ways. The area can be divided into smaller areas and addressed individually, Fig. 4a. The benefit of this method is that several acting points or objects can be monitored at the same time. For these "matrix" type solutions the complexity of the readout electronics increases quickly, when the need for the location resolution increases. A single element of the matrix can be addressed also by using multiplexed amplifier and common row and column electrodes, Fig. 4b. This clearly reduces the number of amplifiers needed. However, the multiplexing rate must be high enough and this might cause problems if the number of matrix elements increases. With the modulator-type capacitive film the other than Fig. 4b-type matrix-type location sensitive solutions are more complex, if the amplitude of the force have to be measured.

Another way to realize location sensitivity in the generator-type sensors is to use resistive electrode material and measure the arising charge at the corners of the film sheet, Fig. 4c. In this case, however, only one acting point for a force at a time can be obtained.

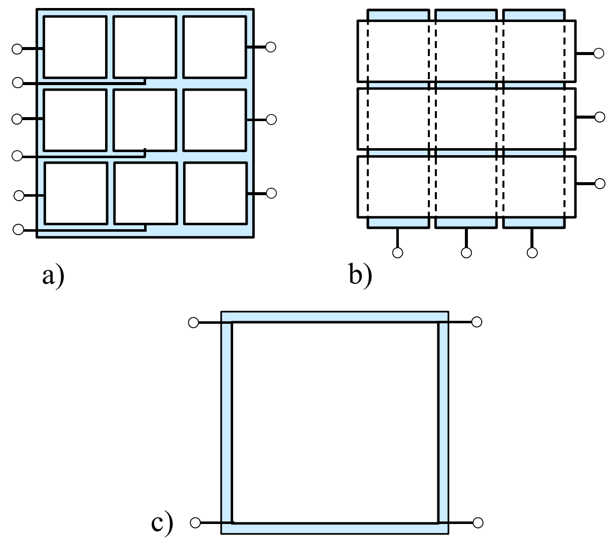

Fig. 4. Possible electrode configurations for location sensitive large area sensors. a) Separately addressed sensing areas, b) common row and column electrodes, and c) resistive electrode.

4. APPLICATIONS

Thin polymer foils can be integrated into various mechanical structures. The necessary deformation needed by the piezoelectric or porous electret film sensors to operate is of the order of tens of nanometers. EMFi has been utilized, for example, in keyboards. The keyboards that are designed for heavy industrial use and have good resistance against vandalism and harsh outdoor environment can be protected with a thick 3–5 mm steel or plastic plate [9].

EMFi material is less expensive than PVDF, which makes it applicable also for large area sensors like floor monitoring systems. The sensing floor consists of an EMFi sheet installed under ordinary flooring for recording footsteps and other movement. Sensitivity of the material is adequate for the floor sensor to be laminated under plastic, wooden or even under ceramic and stone coatings [10].

Floor applications of EMFi include patient monitoring and general surveillance or activity monitoring [10, 11, 12].

VTT Information Technology has developed a Virtual Space concept based on EMFi floor user interface. The Virtual Space project introduces a totally new kind of user interface where players interact with a computer game and with other players through movement. EMFi sensors underneath a 4x4-metre floor area recognise the movements and positions of the players. In addition to the scene projected onto the screen, sound and lighting effects are used to show actions in the game and to create the right atmosphere [13].

Flexible and thin sensors are useful also in some applications where physiological signals (heart rate, breathing) are recorded [14], Figure 5 shows a signal measured from a large EMFi sensor when a person is sitting on it quietly. The signal is a raw signal without any special filtering. The heart pulse can be clearly seen. The pulse is called as ballistocardiogram and it is arising from the recoil movement of the body when the heart is pumping blood.

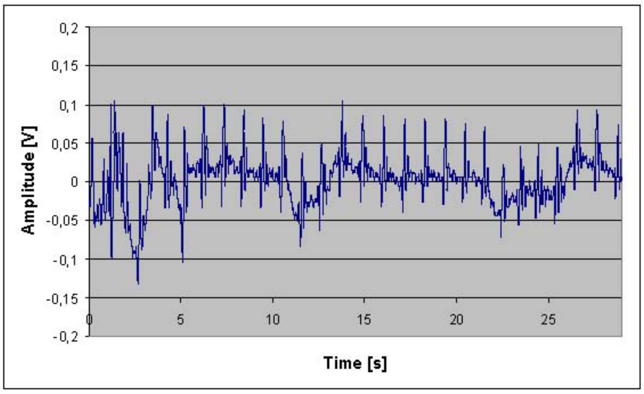

Fig. 5. Ballistocardiographic signal measured from an EMFi sensor.

5. CONCLUSION

Thin porous polymer electret films are promising material for large area sensors in smart environment and ubiquitos sensing. In surveillance and health care applications they can sense movement, activity or some physiological parameters.

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